# Metrology Supporting Deep Ultraviolet Lithography

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***"It's an excellent service NIST has performed for the entire industry. The kind of thing NIST is there for – to identify issues before the train wreck takes place."***

*Mordechai Rothschild, Massachusetts Institute of Technology's Lincoln Laboratory*

## Goals

Develop solutions to key metrology issues confronting the semiconductor lithography industry. These include development of measurement methods and standards for characterizing deep ultraviolet (DUV) laser sources, detectors, and materials. One focus is on delivering high-accuracy measurements of DUV detector parameters and materials properties of immediate need by the industry. There is ongoing activity in the following areas: standards development, calibration services, characteriza-tion of optical materials, sources, and detectors, in addition to advising customers on in-house measurements.

## Customer Needs

Increasing information technology requirements have yielded a strong demand for faster logic circuits and higher-density memory chips. This demand has led to the introduction of DUV laser-based lithographic tools for semiconductor manufacturing. These tools, which employ KrF (248 nm) and ArF (193 nm) excimer lasers, have led to an increased demand for accurate measurements at DUV laser wavelengths. Next generation tools employing $F_2$ (157 nm ) excimer lasers, projected for insertion into production lines by 2005, require even higher accuracy measurements. To support these efforts, the National Institute of Standards and Technology (NIST), with International SEMATECH support, has initiated a DUV metrology program focusing on the characterization of DUV optical materials, sources, and detectors.

*The potential solutions for lithographic systems are discussed in the 2001 International Technology Roadmap for Semiconductors on page 14 of the Lithography Section, and in Figure 34 on page 15. "Optical lithography is the mainstream approach through the 90 nm node,—." The emphasis is on 193 nm and 157 nm light source systems.*

## Technical Strategy

1. Beginning with the first edition of the National Technology Roadmap for Semiconductors (NTRS) in 1992, the semiconductor industry has made an organized, concentrated effort to reduce the feature sizes of integrated circuits. As a result, there has been a continual shift towards shorter exposure wavelengths in the optical lithography process. Because of their inherent characteristics, deep ultraviolet (DUV) lasers, specifically KrF (248 nm) and ArF (193 nm), and more recently $F_2$ (157 nm) excimer lasers, are the preferred sources for high-resolution lithography at this time. To meet the laser metrology needs of the optical lithography community, we have developed primary standards and associated measurement systems at 193 and 248 nm, and are in the process of developing standards at 157 nm measurements, Fig. 1.

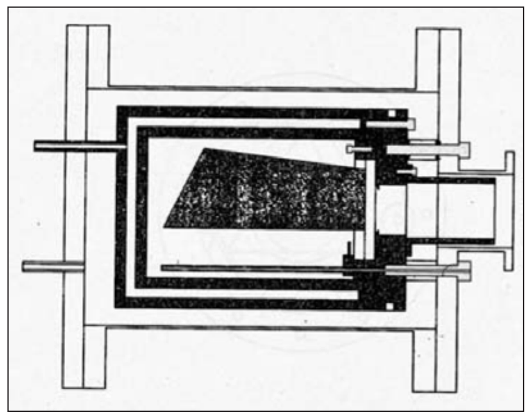

*Figure 1. Excimer laser calorimeter for 157 nm measurements.*

**DELIVERABLES:** Develop a 157 nm excimer laser primary standard and calibration service to provide support for the next generation of optical lithography. 1Q 2003

2. To meet the semiconductor industry's demands for more rapid, accurate measurements of excimer laser power and energy, we are building a system to determine the nonlinear response of an excimer laser detector, Fig. 2. This system uses a correlation method to measure the nonlinear response of pulsed-energy detectors at 248 nm. The response of the detector under test is compared to the corresponding response of a linear monitor detector as a function of incident laser pulse energy. This method addresses the difficulties related to large pulse-to-pulse instability of most excimer laser and delivers measurement results with an expanded uncertainty (k=2) of 0.8 %.

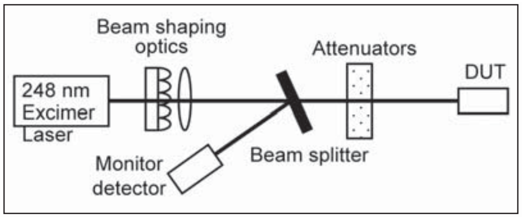


*Figure 2. Schematic diagram of 248 nm nonlinear response system.*

**DELIVERABLES:** Add capability to perform nonlinearity measurements at 248 nm. 4Q 2003

3. High-accuracy measurements of the index properties of UV materials is a requirement for the design of DUV lithography systems. To meet this demand NIST has developed methods to make measurements of the DUV refractive index, as well as its wavelength, temperature, and stress dependencies to the high accuracy needed. Index variations and birefringence have become a limiting factor in the development of the optics for lithography systems, especially at 157 nm. To address this problem we have developed unique VUV polarimetry and Twyman-Green interferometer systems to measure 157 nm index variation in lens materials due both to external stress and grown-in defects.

**DELIVERABLES:** Characterize index inhomogeneities of DUV materials near 157 nm at the sub ppm level. 4Q 2003

4. In the course of our measurements we discovered that in addition to index variations and birefringence due to material defects and external stress, there are also index variations and birefringence *intrinsic* to the material. The commonly-accepted assumption that the cubic symmetry of the crystals used would ensure the isotropy of the optical properties, in fact breaks down due to the finite value of the photon momentum $q$. This previously-neglected effect on ultraviolet optics has a $1/\lambda^2$ wavelength dependence, and is negligible at visible wavelengths, where the index homogeneity and birefringence are measured. However, at 157 nm the effect is large (≈ten times the 157 nm birefringence specification), and this has serious implications on 157 nm lithography system design and performance. This intrinsic birefringence must be accurately characterized for all materials considered for optics in 157 nm systems, including the mixed crystals $Ca_{1-x}Ba_xF_2$ we are co-developing that have the potential of having negligible intrinsic birefringence.

**DELIVERABLES:** Develop and characterize $Ca_{1-x}Sr_xF_2$ mixed crystals, produced to eliminate intrinsic birefringence. 4Q 2003

5. We are developing a new method for measuring the refractive index of transmissive samples to a high accuracy ≈1 ppm in the DUV and VUV using a VUV FT spectrometer. This method is directed to measurements down to 135 nm using synchrotron radiation as a continuum source.

**DELIVERABLES:** Measurements of VUV index properties of optical materials important for the lithography industry, using an interferometric technique in conjunction with SURF III. 4Q 2003

6. Our efforts for complete characterization of the optical properties of materials involve measuring the transmittance, reflectance, surface and bulk scatter, and surface and bulk absorption. This characterization is done on one of the beam lines at the NIST Synchrotron Ultraviolet Radiation Facility (SURF) which is devoted to material and detector characterization in the wavelength range 120 nm – 320 nm. We have used this facility to characterize various samples of calcium fluoride where the transmittance and reflectance was measured with an uncertainty of better than 1%.

SURF III acts as the primary standard for both sources and detectors in the DUV and VUV spectral region.

**DELIVERABLES:** Achieve a 0.1% standard uncertainty of UV irradiance from 3 nm to 400 nm, and enable accurate, direct radiance, and irradiance comparisons with new as well as existing source transfer standards. 4Q 2002

7. Monochromatized radiation from SURF III along with a cryogenic radiometer is used to provide absolute detector-based radiometric calibrations in the spectral range from 125 nm to 320 nm with a standard uncertainty of better than 1%. This facility has also been used to study the degradation in diodes induced by exposure to UV radiation. A wide variety of diodes (Si diodes from Hamamatsu, nitrided Si diodes from IRD, PtSi, GaN, GaP, GaAsP, and diamond) were characterized for spectral responsivity and uniformity mapping, and the degradation in these diodes at 130 nm was also measured.

A new facility for characterizing the degradation of diodes to excimer radiation at 157 has been completed. This facility allows the measurement of the spectral responsivity of the devices in the spectral range from 130 nm to 500 nm along with the measurement of the reflectivity of the diodes as the devices are irradiated by the excimer radiation. This allows identification of potentially stable diodes for UV irradiance measurements. The facility can also be used to characterize other types of detectors such as photochromic films.

**DELIVERABLES:** Characterize the stability of variety of semiconductor diodes to excimer radiation at 157 nm. 2Q 2002

8. We plan to use the synchrotron radiation in conjunction with a cryogenic radiometer to measure the transmittance, reflectance, surface and bulk losses, which would lead to a complete optical characterization of the transmissive samples. Capability will also be developed to make polarization dependent measurements in the spectral range from 125 nm to 320 nm.

**DELIVERABLES:** Build a state of the art facility for an accurate and complete characterization of the optical properties of transmissive materials. 4Q 2002

## ACCOMPLISHMENTS

■ We have developed a system to characterize the nonlinear response of a 193 nm excimer laser detector based on the correlation method. The method and system solves measurement difficulties associated with the temporal and spatial fluctuations of excimer laser pulse energy. The system has a dynamic range of 30 µJ to 50 mJ of pulse energy. The typical measurement uncertainty is 0.8 %. Several DUV detectors were tested. Using this system, one can easily determine the origin of a detector's nonlinear response, such as those due to the incident pulse energy, range discontinuities associated with detector gain, and detector background noise, see Fig. 3. We have discovered detectors having nonlinearity as high as 8 %.

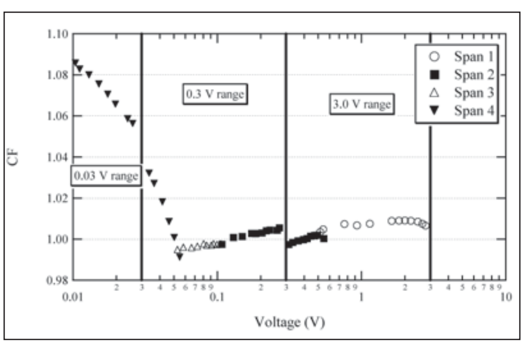


*Figure 3. Nonlinearity measurement result of a 193 nm pulsed laser energy detector. CF is the correction for the detector's nonlinear response. The response is measured in four spans, covering 2.5 meter settings. The large degree of nonlinearity at the low end of the meter range is due to background effects.*

■ We have determined the damage thresholds and lifetimes of several materials using 157 and 193 nm excimer lasers and a beam profile technique similar to ISO 11254-2, Fig. 4. We made these measurements to select an appropriate absorbing material for use in our primary standard laser calorimeter for 157 nm excimer laser power measurements. The materials we tested were nickel-plated sapphire, chemically-vapor-deposited silicon carbide (CVD SiC), nickel-plated copper, and polished copper. Applied pulse energy densities (or dose) ranged from 80 to 840 $mJ/cm^2$. We determined the applied dose from a series of laser beam profile measurements. Silicon carbide had the highest damage threshold: 730 $mJ/cm^2$ per pulse. For this reason, and for its high thermal and electrical conductivities, we have chosen silicon carbide as the absorber material for the 157 nm calorimeter.

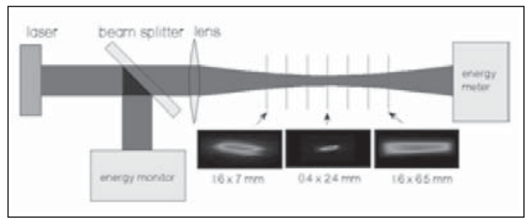


*Figure 4. Damage threshold measurements. Beam profiles were recorded and characterized at 22 planes along the propagation axis using a CCD camera and quantum converter. Three energy density distributions at inner- and outer-most positions, together with their dimensions, are shown. The dimensions are based on the calculation of the second moments according to ISO 11146.*

■ Using a unique UV polarimetry system we developed, we made the first measurements of an intrinsic birefringence in $CaF_2$ and $BaF_2$. These values turned out to be over ten times the 157 nm lithography birefringence target value, and have forced all 157 nm system designs to be substantially redesigned. We developed the complete theory of the effect, now fully accepted, and analyzed its angular dependence. From this we first suggested a compensation approach based on combining lenses of different crystal axis orientations. All 157 nm system designs now utilize this correction approach. We also showed that since the intrinsic birefringence of $CaF_2$ and $BaF_2$ have opposite signs, then a mixed crystal $Ca_{1-x}Ba_xF_2$ can in principle be made which has zero intrinsic birefringence at 157 nm, Fig. 5. We have worked with crystal growers to develop this material and characterize its optical properties.

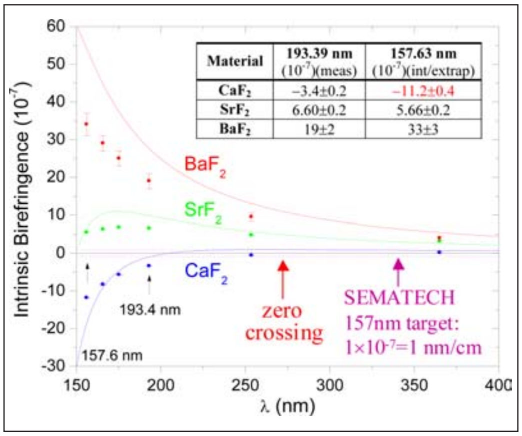


*Figure 5. Measured (symbols) and calculated (curves) intrinsic birefringence of $CaF_2$. $SrF_2$, and $BaF_2$. The figure shows opposite signs of the effect for $CaF_2$, and $SrF_2$ and $BaF_2$.*

■ Immersion lithography has been identified as a possible way to extend the commercial viability of 193 nm lithography technology. However, various technical issues with immersion lithography cannot be resolved without accurate data on the refractive index ($n$) of the immersion fluid (water), and its dependencies on temperature ($dn/dT$), pressure ($dn/dP$), dissolved gas content, and impurities. We have made the first accurate measurements of these index properties of water near 193 nm using both the goniometric method and the interferometric method, with consistency of results. These values are now being used by the semiconductor industry for design of immersion lithography tools.

■ The stability of semiconductor diodes under irradiation from an excimer laser operating at 157 nm has been evaluated. We have built a facility at SURF III that allows simultaneous exposure of photodiodes to excimer radiation, see Fig. 6, and synchrotron radiation. Measurements of the spectral responsivity can be made in the spectral range from 130 nm to 320 nm with a standard uncertainty of less than 1%. The intense, pulsed laser radiation was used to expose the photodiodes for varying amounts of accumulated irradiation whereas the low intensity, continuously-tunable cw radiation from the synchrotron source was used to characterize the photodiodes. The changes in the spectral responsivity of different kinds of diodes such as UV silicon, GaP, GaAsP, PtSi, diamond, and GaN were measured for a large range of total accumulated dose from an $F_2$ excimer laser operating at 157 nm. Differing amounts of changes were seen in different diodes depending on the total excimer irradiation dose and they showed different spectral changes in the responsivity as well. This yields important information about the mechanism responsible for the degradation of photodiodes.

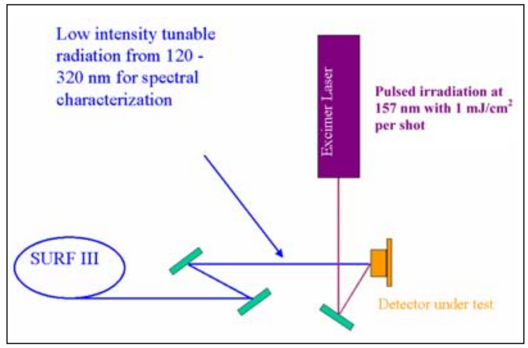


*Figure 6. Photodetector damage experiment for 157 nm radiation.*

■ We have also characterized pyroelectric detectors which are commonly used for high-power laser application. In the vacuum UV to near UV range, pyroelectric detectors are commercially available because of important applications in areas like semiconductor photolithography. Instead of calibrating these detectors using high-power radiation, we performed measurements with low-power UV radiation at beamline 4 of the SURF III. To accommodate the pulse detection nature of the pyroelectric detectors, we installed a 10 Hertz tuning fork chopper at beamline 4 and lock-in amplifiers were used for detector signal processing. Several commercial pyroelectric detectors were tested at our facility. We found that in most cases, the manufacturer-supplied amplifiers were too noisy for our light intensity on the order of one microwatt. Subsequently, a low-noise amplifier was constructed and installed near the detection head. In addition, for several high reflectance pyroelectric detectors, we also measured the reflectance of the pyroelectric element to check the internal quantum efficiency of the detector.

■ We have constructed and characterized a probe that is suitable for accurate measurements of irradiance in the vacuum ultraviolet spectral range. Many industrial applications such as UV curing, photolithography, or semiconductor chip fabrication require accurate measurement of the irradiance and will benefit from having such a stable, accurate UV probe. The probe was characterized at various wavelengths ranging from 157 nm to 325 nm, encompassing many of the important industrial application wavelengths. The principle of measurement of the irradiance is based on scanning the probe in a light field and measuring the spectral responsivity on a grid with regular spacing. Measurement of the spectral responsivity in the center of the probe along with the integrated total responsivity yields the spectral irradiance, Fig. 7. This method can alternatively be used to calculate aperture areas as well by measuring the ratio of the total responsivity and the responsivity in the center.

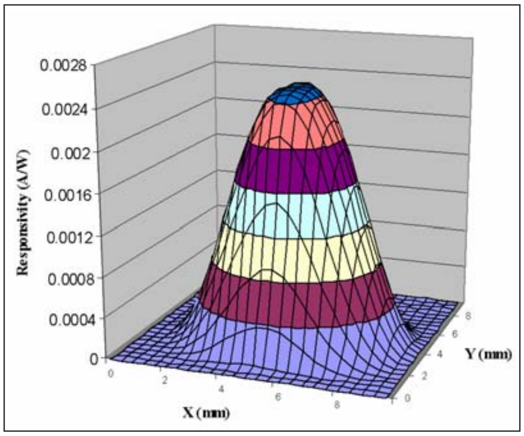


*Figure 7. Measurement of the areal responsivitity of a UV probe at 157 nm.*

## Collaborations

MIT Lincoln Laboratory, Mordechai Rothschild; DUV detector damage, immersion optical fluid measurements.

## Recent Publications


"A Primary Standard for 157 nm Excimer Laser Measurements," C. L. Cromer, M. L. Dowell, R. D. Jones, D. A. Keenan, S. Yang, 2003 Int'l Conf. on Characterization and Metrology for ULSI Tech. (March 2003) *in press*.

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Symmetry of spatial-dispersion-induced birefringence and its implications for $CaF_2$ ultraviolet optics," J. H. Burnett, Z. H. Levine, E. L. Shirley, and J. H. Bruning, Journal of Microlithography, Microfabrication, and Microsystems **1**, pp. 213-224 (2002).

"Measurement of the refractive index and thermo-optic coefficient of water near 193nm," J. H. Burnett and S. Kaplan, to appear in, *Optical Microlithography XVI*, Proceedings of SPIE Vol. 5040 (2003).